

## Observation of $B \rightarrow K\eta\gamma$

K. Abe,<sup>10</sup> K. Abe,<sup>46</sup> N. Abe,<sup>49</sup> I. Adachi,<sup>10</sup> H. Aihara,<sup>48</sup> M. Akatsu,<sup>24</sup> Y. Asano,<sup>53</sup>  
T. Aso,<sup>52</sup> V. Aulchenko,<sup>2</sup> T. Aushev,<sup>14</sup> T. Aziz,<sup>44</sup> S. Bahinipati,<sup>6</sup> A. M. Bakich,<sup>43</sup>  
Y. Ban,<sup>36</sup> M. Barbero,<sup>9</sup> A. Bay,<sup>20</sup> I. Bedny,<sup>2</sup> U. Bitenc,<sup>15</sup> I. Bizjak,<sup>15</sup> S. Blyth,<sup>29</sup>  
A. Bondar,<sup>2</sup> A. Bozek,<sup>30</sup> M. Bračko,<sup>22,15</sup> J. Brodzicka,<sup>30</sup> T. E. Browder,<sup>9</sup> M.-C. Chang,<sup>29</sup>  
P. Chang,<sup>29</sup> Y. Chao,<sup>29</sup> A. Chen,<sup>26</sup> K.-F. Chen,<sup>29</sup> W. T. Chen,<sup>26</sup> B. G. Cheon,<sup>4</sup>  
R. Chistov,<sup>14</sup> S.-K. Choi,<sup>8</sup> Y. Choi,<sup>42</sup> Y. K. Choi,<sup>42</sup> A. Chuvikov,<sup>37</sup> S. Cole,<sup>43</sup>  
M. Danilov,<sup>14</sup> M. Dash,<sup>55</sup> L. Y. Dong,<sup>12</sup> R. Dowd,<sup>23</sup> J. Dragic,<sup>23</sup> A. Drutskoy,<sup>6</sup>  
S. Eidelman,<sup>2</sup> Y. Enari,<sup>24</sup> D. Epifanov,<sup>2</sup> C. W. Everton,<sup>23</sup> F. Fang,<sup>9</sup> S. Fratina,<sup>15</sup>  
H. Fujii,<sup>10</sup> N. Gabyshev,<sup>2</sup> A. Garmash,<sup>37</sup> T. Gershon,<sup>10</sup> A. Go,<sup>26</sup> G. Gokhroo,<sup>44</sup>  
B. Golob,<sup>21,15</sup> M. Grosse Perdekamp,<sup>38</sup> H. Guler,<sup>9</sup> J. Haba,<sup>10</sup> F. Handa,<sup>47</sup> K. Hara,<sup>10</sup>  
T. Hara,<sup>34</sup> N. C. Hastings,<sup>10</sup> K. Hasuko,<sup>38</sup> K. Hayasaka,<sup>24</sup> H. Hayashii,<sup>25</sup> M. Hazumi,<sup>10</sup>  
E. M. Heenan,<sup>23</sup> I. Higuchi,<sup>47</sup> T. Higuchi,<sup>10</sup> L. Hinz,<sup>20</sup> T. Hojo,<sup>34</sup> T. Hokuue,<sup>24</sup>  
Y. Hoshi,<sup>46</sup> K. Hoshina,<sup>51</sup> S. Hou,<sup>26</sup> W.-S. Hou,<sup>29</sup> Y. B. Hsiung,<sup>29</sup> H.-C. Huang,<sup>29</sup>  
T. Igaki,<sup>24</sup> Y. Igarashi,<sup>10</sup> T. Iijima,<sup>24</sup> A. Imoto,<sup>25</sup> K. Inami,<sup>24</sup> A. Ishikawa,<sup>10</sup> H. Ishino,<sup>49</sup>  
K. Itoh,<sup>48</sup> R. Itoh,<sup>10</sup> M. Iwamoto,<sup>3</sup> M. Iwasaki,<sup>48</sup> Y. Iwasaki,<sup>10</sup> R. Kagan,<sup>14</sup> H. Kakuno,<sup>48</sup>  
J. H. Kang,<sup>56</sup> J. S. Kang,<sup>17</sup> P. Kapusta,<sup>30</sup> S. U. Kataoka,<sup>25</sup> N. Katayama,<sup>10</sup> H. Kawai,<sup>3</sup>  
H. Kawai,<sup>48</sup> Y. Kawakami,<sup>24</sup> N. Kawamura,<sup>1</sup> T. Kawasaki,<sup>32</sup> N. Kent,<sup>9</sup> H. R. Khan,<sup>49</sup>  
A. Kibayashi,<sup>49</sup> H. Kichimi,<sup>10</sup> H. J. Kim,<sup>19</sup> H. O. Kim,<sup>42</sup> Hyunwoo Kim,<sup>17</sup> J. H. Kim,<sup>42</sup>  
S. K. Kim,<sup>41</sup> T. H. Kim,<sup>56</sup> K. Kinoshita,<sup>6</sup> P. Koppenburg,<sup>10</sup> S. Korpar,<sup>22,15</sup> P. Krizan,<sup>21,15</sup>  
P. Krokovny,<sup>2</sup> R. Kulasiri,<sup>6</sup> C. C. Kuo,<sup>26</sup> H. Kurashiro,<sup>49</sup> E. Kurihara,<sup>3</sup> A. Kusaka,<sup>48</sup>  
A. Kuzmin,<sup>2</sup> Y.-J. Kwon,<sup>56</sup> J. S. Lange,<sup>7</sup> G. Leder,<sup>13</sup> S. E. Lee,<sup>41</sup> S. H. Lee,<sup>41</sup>  
Y.-J. Lee,<sup>29</sup> T. Lesiak,<sup>30</sup> J. Li,<sup>40</sup> A. Limosani,<sup>23</sup> S.-W. Lin,<sup>29</sup> D. Liventsev,<sup>14</sup>  
J. MacNaughton,<sup>13</sup> G. Majumder,<sup>44</sup> F. Mandl,<sup>13</sup> D. Marlow,<sup>37</sup> T. Matsuiishi,<sup>24</sup>  
H. Matsumoto,<sup>32</sup> S. Matsumoto,<sup>5</sup> T. Matsumoto,<sup>50</sup> A. Matyja,<sup>30</sup> Y. Mikami,<sup>47</sup>  
W. Mitaroff,<sup>13</sup> K. Miyabayashi,<sup>25</sup> Y. Miyabayashi,<sup>24</sup> H. Miyake,<sup>34</sup> H. Miyata,<sup>32</sup> R. Mizuk,<sup>14</sup>  
D. Mohapatra,<sup>55</sup> G. R. Moloney,<sup>23</sup> G. F. Moorhead,<sup>23</sup> T. Mori,<sup>49</sup> A. Murakami,<sup>39</sup>  
T. Nagamine,<sup>47</sup> Y. Nagasaka,<sup>11</sup> T. Nakadaira,<sup>48</sup> I. Nakamura,<sup>10</sup> E. Nakano,<sup>33</sup> M. Nakao,<sup>10</sup>  
H. Nakazawa,<sup>10</sup> Z. Natkaniec,<sup>30</sup> K. Neichi,<sup>46</sup> S. Nishida,<sup>10</sup> O. Nitoh,<sup>51</sup> S. Noguchi,<sup>25</sup>  
T. Nozaki,<sup>10</sup> A. Ogawa,<sup>38</sup> S. Ogawa,<sup>45</sup> T. Ohshima,<sup>24</sup> T. Okabe,<sup>24</sup> S. Okuno,<sup>16</sup>  
S. L. Olsen,<sup>9</sup> Y. Onuki,<sup>32</sup> W. Ostrowicz,<sup>30</sup> H. Ozaki,<sup>10</sup> P. Pakhlov,<sup>14</sup> H. Palka,<sup>30</sup>  
C. W. Park,<sup>42</sup> H. Park,<sup>19</sup> K. S. Park,<sup>42</sup> N. Parslow,<sup>43</sup> L. S. Peak,<sup>43</sup> M. Pernicka,<sup>13</sup>  
J.-P. Perroud,<sup>20</sup> M. Peters,<sup>9</sup> L. E. Piilonen,<sup>55</sup> A. Poluektov,<sup>2</sup> F. J. Ronga,<sup>10</sup> N. Root,<sup>2</sup>  
M. Rozanska,<sup>30</sup> H. Sagawa,<sup>10</sup> M. Saigo,<sup>47</sup> S. Saitoh,<sup>10</sup> Y. Sakai,<sup>10</sup> H. Sakamoto,<sup>18</sup>  
T. R. Sarangi,<sup>10</sup> M. Satapathy,<sup>54</sup> N. Sato,<sup>24</sup> O. Schneider,<sup>20</sup> J. Schümann,<sup>29</sup> C. Schwanda,<sup>13</sup>  
A. J. Schwartz,<sup>6</sup> T. Seki,<sup>50</sup> S. Semenov,<sup>14</sup> K. Senyo,<sup>24</sup> Y. Settai,<sup>5</sup> R. Seuster,<sup>9</sup>  
M. E. Sevier,<sup>23</sup> T. Shibata,<sup>32</sup> H. Shibuya,<sup>45</sup> B. Shwartz,<sup>2</sup> V. Sidorov,<sup>2</sup> V. Siegle,<sup>38</sup>  
J. B. Singh,<sup>35</sup> A. Somov,<sup>6</sup> N. Soni,<sup>35</sup> R. Stamen,<sup>10</sup> S. Stanič,<sup>53,\*</sup> M. Starič,<sup>15</sup> A. Sugi,<sup>24</sup>  
A. Sugiyama,<sup>39</sup> K. Sumisawa,<sup>34</sup> T. Sumiyoshi,<sup>50</sup> S. Suzuki,<sup>39</sup> S. Y. Suzuki,<sup>10</sup> O. Tajima,<sup>10</sup>  
F. Takasaki,<sup>10</sup> K. Tamai,<sup>10</sup> N. Tamura,<sup>32</sup> K. Tanabe,<sup>48</sup> M. Tanaka,<sup>10</sup> G. N. Taylor,<sup>23</sup>  
Y. Teramoto,<sup>33</sup> X. C. Tian,<sup>36</sup> S. Tokuda,<sup>24</sup> S. N. Tovey,<sup>23</sup> K. Trabelsi,<sup>9</sup> T. Tsuboyama,<sup>10</sup>

T. Tsukamoto,<sup>10</sup> K. Uchida,<sup>9</sup> S. Uehara,<sup>10</sup> T. Uglov,<sup>14</sup> K. Ueno,<sup>29</sup> Y. Unno,<sup>3</sup> S. Uno,<sup>10</sup>  
Y. Ushiroda,<sup>10</sup> G. Varner,<sup>9</sup> K. E. Varvell,<sup>43</sup> S. Villa,<sup>20</sup> C. C. Wang,<sup>29</sup> C. H. Wang,<sup>28</sup>  
J. G. Wang,<sup>55</sup> M.-Z. Wang,<sup>29</sup> M. Watanabe,<sup>32</sup> Y. Watanabe,<sup>49</sup> L. Widhalm,<sup>13</sup>  
Q. L. Xie,<sup>12</sup> B. D. Yabsley,<sup>55</sup> A. Yamaguchi,<sup>47</sup> H. Yamamoto,<sup>47</sup> S. Yamamoto,<sup>50</sup>  
T. Yamanaka,<sup>34</sup> Y. Yamashita,<sup>31</sup> M. Yamauchi,<sup>10</sup> Heyoung Yang,<sup>41</sup> P. Yeh,<sup>29</sup> J. Ying,<sup>36</sup>  
K. Yoshida,<sup>24</sup> Y. Yuan,<sup>12</sup> Y. Yusa,<sup>47</sup> H. Yuta,<sup>1</sup> S. L. Zang,<sup>12</sup> C. C. Zhang,<sup>12</sup> J. Zhang,<sup>10</sup>  
L. M. Zhang,<sup>40</sup> Z. P. Zhang,<sup>40</sup> V. Zhilich,<sup>2</sup> T. Ziegler,<sup>37</sup> D. Žontar,<sup>21, 15</sup> and D. Zürcher<sup>20</sup>

(The Belle Collaboration)

<sup>1</sup>*Aomori University, Aomori*

<sup>2</sup>*Budker Institute of Nuclear Physics, Novosibirsk*

<sup>3</sup>*Chiba University, Chiba*

<sup>4</sup>*Chonnam National University, Kwangju*

<sup>5</sup>*Chuo University, Tokyo*

<sup>6</sup>*University of Cincinnati, Cincinnati, Ohio 45221*

<sup>7</sup>*University of Frankfurt, Frankfurt*

<sup>8</sup>*Gyeongsang National University, Chinju*

<sup>9</sup>*University of Hawaii, Honolulu, Hawaii 96822*

<sup>10</sup>*High Energy Accelerator Research Organization (KEK), Tsukuba*

<sup>11</sup>*Hiroshima Institute of Technology, Hiroshima*

<sup>12</sup>*Institute of High Energy Physics,*

*Chinese Academy of Sciences, Beijing*

<sup>13</sup>*Institute of High Energy Physics, Vienna*

<sup>14</sup>*Institute for Theoretical and Experimental Physics, Moscow*

<sup>15</sup>*J. Stefan Institute, Ljubljana*

<sup>16</sup>*Kanagawa University, Yokohama*

<sup>17</sup>*Korea University, Seoul*

<sup>18</sup>*Kyoto University, Kyoto*

<sup>19</sup>*Kyungpook National University, Taegu*

<sup>20</sup>*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*

<sup>21</sup>*University of Ljubljana, Ljubljana*

<sup>22</sup>*University of Maribor, Maribor*

<sup>23</sup>*University of Melbourne, Victoria*

<sup>24</sup>*Nagoya University, Nagoya*

<sup>25</sup>*Nara Women's University, Nara*

<sup>26</sup>*National Central University, Chung-li*

<sup>27</sup>*National Kaohsiung Normal University, Kaohsiung*

<sup>28</sup>*National United University, Miao Li*

<sup>29</sup>*Department of Physics, National Taiwan University, Taipei*

<sup>30</sup>*H. Niewodniczanski Institute of Nuclear Physics, Krakow*

<sup>31</sup>*Nihon Dental College, Niigata*

<sup>32</sup>*Niigata University, Niigata*

<sup>33</sup>*Osaka City University, Osaka*

<sup>34</sup>*Osaka University, Osaka*

<sup>35</sup>*Panjab University, Chandigarh*

<sup>36</sup>*Peking University, Beijing*

<sup>37</sup>*Princeton University, Princeton, New Jersey 08545*

<sup>38</sup>*RIKEN BNL Research Center, Upton, New York 11973*

<sup>39</sup>*Saga University, Saga*

<sup>40</sup>*University of Science and Technology of China, Hefei*

<sup>41</sup>*Seoul National University, Seoul*

<sup>42</sup>*Sungkyunkwan University, Suwon*

<sup>43</sup>*University of Sydney, Sydney NSW*

<sup>44</sup>*Tata Institute of Fundamental Research, Bombay*

<sup>45</sup>*Toho University, Funabashi*

<sup>46</sup>*Tohoku Gakuin University, Tagajo*

<sup>47</sup>*Tohoku University, Sendai*

<sup>48</sup>*Department of Physics, University of Tokyo, Tokyo*

<sup>49</sup>*Tokyo Institute of Technology, Tokyo*

<sup>50</sup>*Tokyo Metropolitan University, Tokyo*

<sup>51</sup>*Tokyo University of Agriculture and Technology, Tokyo*

<sup>52</sup>*Toyama National College of Maritime Technology, Toyama*

<sup>53</sup>*University of Tsukuba, Tsukuba*

<sup>54</sup>*Utkal University, Bhubaneswer*

<sup>55</sup>*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*

<sup>56</sup>*Yonsei University, Seoul*

## Abstract

We report measurements of radiative  $B$  decays with  $K\eta\gamma$  final states, using a data sample of  $140\text{ fb}^{-1}$  recorded at the  $\Upsilon(4S)$  resonance with the Belle detector at the KEKB  $e^+e^-$  asymmetric energy collider. We observe  $B \rightarrow K\eta\gamma$  for the first time with a branching fraction of  $(6.9^{+1.7}_{-1.6}(\text{stat})^{+1.3}_{-1.0}(\text{syst})) \times 10^{-6}$  for  $M_{K\eta} < 2.4\text{ GeV}/c^2$ . We also set an upper limit on  $B \rightarrow K_3^*(1780)\gamma$ .

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Radiative  $B$  decays, which proceed mainly through the  $b \rightarrow s\gamma$  process [1], have played an important role in the search for physics beyond the Standard Model (SM). Although the inclusive branching fraction has been measured to be  $(3.3 \pm 0.4) \times 10^{-4}$  [2], we know little about its constituents. So far, measured exclusive final states such as  $K^*(892)\gamma$  [3, 4],  $K_2^*(1430)\gamma$  [3, 5],  $K\pi\pi\gamma$  [5] and  $B \rightarrow K\phi\gamma$  [6] only explain one third of the inclusive rate. Detailed knowledge of exclusive final states reduces the theoretical uncertainty in the measurement of the inclusive branching fraction using the pseudo-reconstruction technique, as well as in the measurement of  $B \rightarrow X_s\ell^+\ell^-$  [7]. In this analysis, the decay mode  $B \rightarrow K\eta\gamma$  is studied for the first time. In addition to improving the understanding of  $b \rightarrow s\gamma$  final states,  $B^0 \rightarrow K_S^0\eta\gamma$  can be used to study time-dependent  $CP$  asymmetry [8], which is sensitive to physics beyond the SM. The mode  $B \rightarrow K\eta\gamma$  can also be used to search for  $B \rightarrow K_3^*(1780)\gamma$  via  $K_3^*(1780) \rightarrow K\eta$  decay.

The analysis is based on  $140 \text{ fb}^{-1}$  of data taken at the  $\Upsilon(4S)$  resonance (on-resonance) and  $15 \text{ fb}^{-1}$  at an energy 60 MeV below the resonance (off-resonance), which were recorded by the Belle detector [9] at the KEKB asymmetric  $e^+e^-$  collider (3.5 GeV on 8 GeV) [10]. The on-resonance data corresponds to 152 million  $B\bar{B}$  events. The Belle detector has a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An instrumented iron flux-return for  $K_L/\mu$  detection is located outside the coil.

We reconstruct  $B^+ \rightarrow K^+\eta\gamma$  and  $B^0 \rightarrow K_S^0\eta\gamma$  via  $\eta \rightarrow \gamma\gamma$  and  $\eta \rightarrow \pi^+\pi^-\pi^0$ . All the charged tracks used in the reconstruction (except charged pions from  $K_S^0$ ) are required to have an impact parameter within  $\pm 5 \text{ cm}$  of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. Primary charged kaons are also required to have a momentum in the  $e^+e^-$  center-of-mass (CM) frame that is greater than  $100 \text{ MeV}/c$ . In order to identify kaon and pion candidates, we use a likelihood ratio based on the light yield in the ACC, the TOF information and the specific ionization measurements in the CDC. For the selection applied on the likelihood ratio, we obtain an efficiency (pion misidentification probability) of 90% (9%) for charged kaon candidates, and an efficiency (kaon misidentification probability) of 98% (9%) for charged pion candidates.

$K_S^0$  candidates are formed from  $\pi^+\pi^-$  combinations whose invariant mass is within  $8 \text{ MeV}/c^2$  of the nominal  $K_S^0$  mass. The two pions are required to have a common vertex that is displaced from the interaction point. The  $K_S^0$  momentum direction is also required to be consistent with the  $K_S^0$  flight direction. Neutral pion candidates are formed from pairs of photons that have an invariant mass within  $16 \text{ MeV}/c^2$  of the nominal  $\pi^0$  mass and an energy greater than 100 MeV in the CM frame. Each photon is required to have an energy greater than 50 MeV. A mass constrained fit is then performed to obtain the  $\pi^0$  momentum.

$\eta$  candidates are reconstructed via  $\eta \rightarrow \gamma\gamma$  or  $\eta \rightarrow \pi^+\pi^-\pi^0$ . For  $\eta \rightarrow \gamma\gamma$ , we require that the invariant mass of the two photons satisfy  $0.515 \text{ GeV}/c^2 < M_{\gamma\gamma} < 0.570 \text{ GeV}/c^2$  and that each photon have an energy greater than 50 MeV. We also require that the  $\eta$  decay helicity angle  $\theta_{\text{hel}}$  satisfies  $|\cos \theta_{\text{hel}}| < 0.9$ . A mass constrained fit is then performed to obtain the  $\eta$  momentum. For  $\eta \rightarrow \pi^+\pi^-\pi^0$ , we apply a selection on the  $M_{\pi^+\pi^-\pi^0}$  invariant mass,  $0.532 \text{ GeV}/c^2 < M_{\pi^+\pi^-\pi^0} < 0.562 \text{ GeV}/c^2$ .

We combine a charged or neutral kaon with an  $\eta$  to form a  $K\eta$  system with invariant mass less than  $2.4 \text{ GeV}/c^2$ . We then reconstruct  $B$  meson candidates from the  $K\eta$  system and the highest energy photon with a CM energy between 1.8 GeV and 3.4 GeV within

the acceptance of the barrel ECL ( $33^\circ < \theta_\gamma < 128^\circ$ , where  $\theta_\gamma$  is the polar angle of the photon in the laboratory frame). The photon candidate is required to be consistent with an isolated electromagnetic shower, i.e. 95% of its energy should be concentrated in an array of  $3 \times 3$  crystals and no charged tracks should be associated with it. In order to reduce the background from decays of  $\pi^0$  and  $\eta$  mesons, we combine the photon candidate with all other photons in the event and reject the event if the invariant mass of any pair is within  $18 \text{ MeV}/c^2$  ( $32 \text{ MeV}/c^2$ ) of the nominal  $\pi^0$  ( $\eta$ ) mass (this condition is referred to as the  $\pi^0/\eta$  veto).

We use two independent kinematic variables for the  $B$  reconstruction: the beam-energy constrained mass  $M_{bc} \equiv \sqrt{(E_{\text{beam}}^*/c^2)^2 - (|\vec{p}_{K\eta}^* + \vec{p}_\gamma^*|/c)^2}$  and  $\Delta E \equiv E_{K\eta}^* + E_\gamma^* - E_{\text{beam}}^*$ , where  $E_{\text{beam}}^*$  is the beam energy, and  $\vec{p}_\gamma^*$ ,  $E_\gamma^*$ ,  $\vec{p}_{K\eta}^*$ ,  $E_{K\eta}^*$  are the momenta and energies of the photon and the  $K\eta$  system, respectively, calculated in the CM frame. In the  $M_{bc}$  calculation, the photon momentum is rescaled so that  $|\vec{p}_\gamma^*| = (E_{\text{beam}}^* - E_{K\eta}^*)/c$  is satisfied. We require  $M_{bc} > 5.2 \text{ GeV}/c^2$  and  $-150 \text{ MeV} < \Delta E < 80 \text{ MeV}$ . We define the signal region to be  $M_{bc} > 5.27 \text{ GeV}/c^2$ . In the case that multiple candidates are found in the same event, we take the candidate that has the  $\eta$  mass closest to the nominal mass (and smallest  $|\Delta E|$ ) after applying the background suppression described later.

The largest source of background originates from continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) production including contributions from initial state radiation ( $e^+e^- \rightarrow q\bar{q}\gamma$ ). In order to suppress this background, we use the likelihood ratio (LR) described in Ref. [5], which utilizes the information from a Fisher discriminant [11] formed from six modified Fox-Wolfram moments [12] and the cosine of the angle between the  $B$  meson flight direction and the beam axis. The LR selection retains 44% of the signal, rejecting 98% of the continuum background.

In order to extract the signal yield, we perform a binned likelihood fit to the  $M_{bc}$  distribution. The  $M_{bc}$  distribution of the signal component is modeled by a Crystal Ball line shape [13], where the parameters are determined from the signal MC and calibrated by  $B \rightarrow D\pi$  decays, as described below. The  $M_{bc}$  distribution of the continuum background is modeled by an ARGUS function [14] whose shape is determined from the off-resonance data. Here, the LR selection is not applied to the off-resonance data in order to compensate for the limited amount of data in that sample. The possible bias due to this is taken as systematic error to the fitted yield. Background from  $B$  decays is divided into two components, which we refer to as  $B\bar{B}$  background and rare  $B$  background in this paper. The former comprises  $B$  decays through  $b \rightarrow c$  transitions including color-suppressed  $B$  decays such as  $B^0 \rightarrow \bar{D}^0\pi^0$ , and the latter covers charmless  $B$  decays through  $b \rightarrow s$  and  $b \rightarrow u$  transitions. Each of them is modeled by another ARGUS function. The shape of the distributions is determined by a corresponding Monte Carlo (MC) sample. In order to study the contamination from other  $b \rightarrow s\gamma$  decays, we examine a  $B \rightarrow K^*(892)\gamma$  MC sample and an inclusive  $b \rightarrow s\gamma$  MC sample that is modeled as an equal mixture of  $s\bar{d}$  and  $s\bar{u}$  quark pairs and is hadronized using JETSET [15], where the  $M_{X_s}$  spectrum is fitted to the model of Kagan and Neubert [16]. We find that the feed-down from other  $b \rightarrow s\gamma$  decays is not negligible, and its  $M_{bc}$  distribution is also modeled by an ARGUS function.

Figures 1 (a)-(c) show the  $M_{bc}$  distributions for  $B^+ \rightarrow K^+\eta\gamma$ ,  $B^0 \rightarrow K_S^0\eta\gamma$  and combined  $B \rightarrow K\eta\gamma$ . The distributions are fitted with signal, continuum,  $B\bar{B}$ , rare  $B$  background and the  $b \rightarrow s\gamma$  feed-down components. In the fit, the normalization of  $B\bar{B}$ , rare  $B$  and  $b \rightarrow s\gamma$  are fixed according to the luminosity and  $b \rightarrow s\gamma$  branching fraction, while the normalization of the continuum component is allowed to float. We find the signal yields to

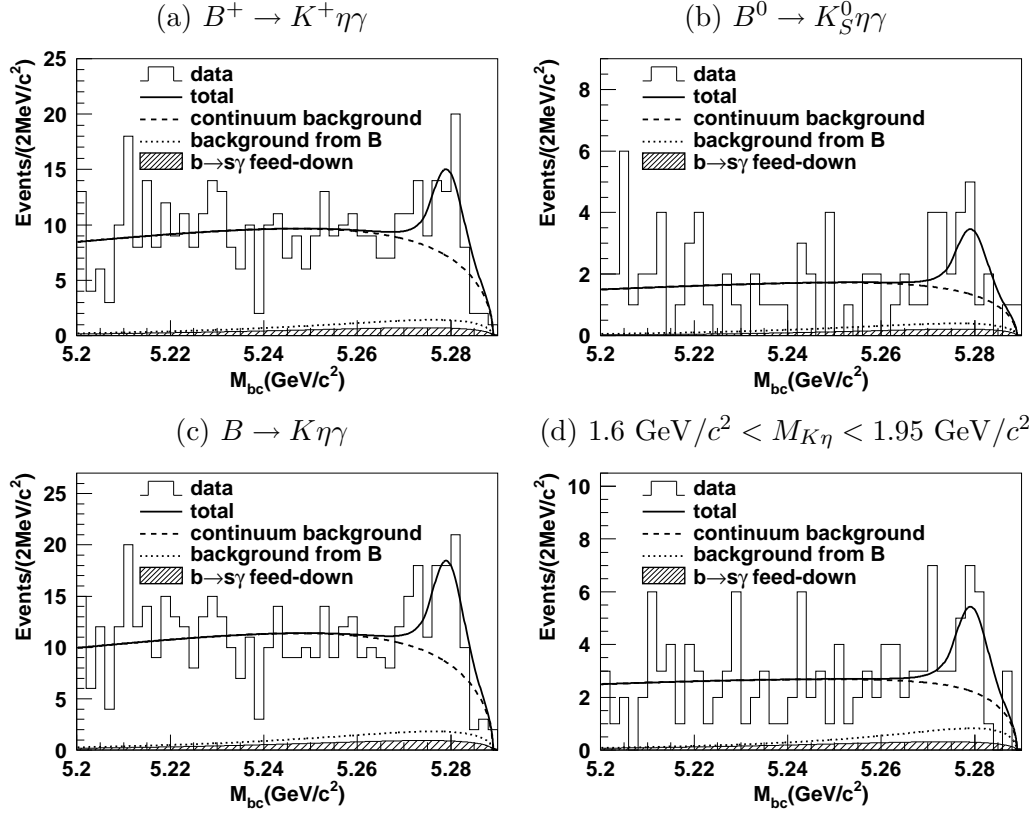


FIG. 1:  $M_{bc}$  distributions for (a)  $B^+ \rightarrow K^+\eta\gamma$ , (b)  $B^0 \rightarrow K_S^0\eta\gamma$ , (c)  $B \rightarrow K\eta\gamma$  (combined  $B^+ \rightarrow K^+\eta\gamma$  and  $B^0 \rightarrow K_S^0\eta\gamma$ ), and (d)  $B \rightarrow K\eta\gamma$  with the mass range for  $B \rightarrow K_3^*(1780)\gamma$ . Fit results are overlaid.

be  $35.5^{+10.1}_{-9.4}$ ,  $9.7^{+5.1}_{-4.3}$  and  $45.0^{+11.2}_{-10.4}$  with statistical significances of  $4.3\sigma$ ,  $2.5\sigma$  and  $5.0\sigma$ , for the charged, neutral and combined modes, respectively. Here, the significance is defined as  $\sqrt{-2\ln(\mathcal{L}(0)/\mathcal{L}_{\max})}$ , where  $\mathcal{L}_{\max}$  is the maximum of the likelihood and  $\mathcal{L}(0)$  is the likelihood for zero signal yield.

The  $K\eta$  invariant mass distribution for events inside the signal region is shown in Fig. 2. Here, the background distributions are obtained from the corresponding MC samples, and are normalized using the fit result. We find that signal excess is concentrated between  $1.3 \text{ GeV}/c^2$  and  $1.9 \text{ GeV}/c^2$ . Therefore, our selection  $M_{K\eta} < 2.4 \text{ GeV}/c^2$  is expected to include most of the  $B \rightarrow K\eta\gamma$  signal. We do not see any clear resonant structure in the  $M_{K\eta}$  distribution.

The systematic error on the signal yield due to the fitting procedure is estimated by varying the value of each fixed parameter by  $\pm 1\sigma$  and extracting the new signal yield for each case. The difference between the background shape for the continuum MC with and without the LR selection is taken as an additional error to the continuum background shape. We set the normalization of either the  $B\bar{B}$  or rare  $B$  backgrounds to zero and to twice its nominal value to account for its uncertainty. The changes of the yields for each procedure are added in quadrature, and are regarded as the systematic error on the signal yield.

The signal reconstruction efficiency is estimated using the MC simulation and is corrected for discrepancies between data and MC using control samples. We find that the efficiency

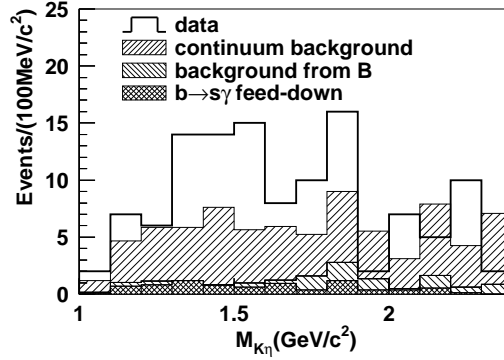


FIG. 2:  $K\eta$  invariant mass distribution for events in the signal regions for  $B \rightarrow K\eta\gamma$

is almost independent of the  $K\eta$  invariant mass. Table I shows the signal efficiencies and the branching fractions for each  $B \rightarrow K\eta\gamma$  mode. Here, we assume an equal production rate for  $B^0\bar{B}^0$  and  $B^+B^-$ . The error includes the following systematic uncertainties: photon detection (2.8%), tracking (1% track), kaon identification (0.8%), pion identification (0.5% per pion),  $K_S^0$  detection (4.5%),  $\pi^0$  detection (1.5%),  $\eta$  detection in  $\eta \rightarrow \gamma\gamma$  mode (2.0%),  $\pi^0/\eta$  veto and LR (3.2% and 9.0% for charged and neutral modes, respectively), possible  $K\eta$  mass dependence of the efficiency (2.1% and 8.4% for charged and neutral modes, respectively), and uncertainty in the  $\eta$  branching fraction (0.7% for  $\eta \rightarrow \gamma\gamma$  and 1.8% for  $\eta \rightarrow \pi^+\pi^-\pi^0$ ). The systematic errors from the  $\pi^0/\eta$  veto and LR requirement are estimated using the  $B^- \rightarrow D^0(\rightarrow K^-\pi^+\pi^0)\pi^-$  and  $B^0 \rightarrow D^-(\rightarrow K_S^0\pi^-\pi^0)\pi^+$  as a control sample, treating the primary pion as a high energy photon. This sample is also used to obtain the  $M_{bc}$  shape of the signal component.

We also search for the decay  $B \rightarrow K_3^*(1780)\gamma$  by applying the additional requirement  $1.60 \text{ GeV}/c^2 < M_{K\eta} < 1.95 \text{ GeV}/c^2$ . The fits to the  $M_{bc}$  distributions yield  $10.5_{-4.8}^{+5.6}$ ,  $4.2_{-2.4}^{+3.2}$  and  $15.0_{-5.5}^{+6.3}$  events for charged, neutral and combined modes, respectively [17]. The  $M_{bc}$  distribution and fit result for the combined mode is shown in Fig. 1 (d). However, we provide only upper limits due to our inability to distinguish  $B \rightarrow K_3^*(1780)\gamma$  from non-resonant decays. The 90% confidence level upper limit  $N$  is calculated from the relation  $\int_0^N \mathcal{L}(n)dn = 0.9 \int_0^\infty \mathcal{L}(n)dn$ , where  $\mathcal{L}(n)$  is the maximum likelihood in the  $M_{bc}$  fit with the signal yield fixed at  $n$ . In order to include the systematic errors from the fitting procedure in the upper limit for the yield, the positive systematic error is added to  $N$ . The obtained yield upper limits, efficiencies and branching fractions are listed in Table I. Here, the error for the efficiency also includes the uncertainty in the  $K_3^*(1780) \rightarrow K\eta$  branching fraction ( $(30 \pm 13)\%$ ). The measurement improves the limits set by the ARGUS collaboration [18].

In conclusion, we observe the decay mode  $B \rightarrow K\eta\gamma$  with a branching fraction of  $(6.9_{-1.6}^{+1.7}(\text{stat})_{-1.0}^{+1.3}(\text{syst})) \times 10^{-6}$  for  $M_{K\eta} < 2.4 \text{ GeV}/c^2$ . We also set upper limits on  $B \rightarrow K_3^*(1780)\gamma$ . Although the signal yield of  $B^0 \rightarrow K_S^0\eta\gamma$  is small, in future this mode can be used to study time-dependent  $CP$  asymmetry in radiative  $B$  decays and to search for new physics.

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TABLE I: Measured signal yields, efficiencies, branching fractions ( $\mathcal{B}$ ), and statistical significances (snf.) [17]. Efficiencies include the sub-decay branching fractions. Upper limits are calculated at the 90% confidence level and include systematics.

Mode	Yield	Efficiency (%)	$\mathcal{B} (\times 10^{-6})$	snf.
$B^+ \rightarrow K^+ \eta \gamma$	$35.5^{+10.1+5.6}_{-9.4-3.9}$	$3.40 \pm 0.20$	$6.9^{+2.0+1.2}_{-1.8-0.9}$	4.3
$B^0 \rightarrow K^0 \eta \gamma$	$9.7^{+5.1+1.6}_{-4.3-1.5}$	$0.88 \pm 0.12$	$7.3^{+3.8+1.6}_{-3.2-1.5}$	2.5
$B \rightarrow K \eta \gamma$	$45.0^{+11.2+7.4}_{-10.4-5.1}$	$4.28 \pm 0.25$	$6.9^{+1.7+1.3}_{-1.6-1.0}$	5.0
$B^+ \rightarrow K_3^*(1780)^+ \gamma$	$< 21.5$	$0.77 \pm 0.34$	$< 33$	—
$B^0 \rightarrow K_3^*(1780)^0 \gamma$	$< 10.0$	$0.17 \pm 0.08$	$< 72$	—
$B \rightarrow K_3^*(1780) \gamma$	$< 27.3$	$0.94 \pm 0.41$	$< 34$	—

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\* on leave from Nova Gorica Polytechnic, Nova Gorica

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